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## Gas outflows in radio galaxies

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### Abstract.

We present a summary of our recent results on gas outflows in radio galaxies. Fast outflows (up to  $2000 \text{ km s}^{-1}$ ) have been detected both in ionized and neutral gas. The latter is particularly surprising as it shows that, despite the extremely energetic phenomena occurring near an AGN, some of the outflowing gas remains, or becomes again, neutral. These results are giving new and important insights on the physical conditions of the gaseous medium around an AGN.

## 1. Introduction

Fast nuclear gas outflows appear to be a relatively common phenomena in active galactic nuclei (AGNs). They have been detected - using optical, UV and X-ray observations - in Seyfert galaxies (see for some examples Crenshaw et al. 2000; Aoki et al. 1996; Capetti et al. 1999 and refs therein), quasars (see e.g. Turnshek 1986, Krongold et al. 2003 and refs therein), but also in starburst galaxies (Veilleux et al. 2002, 2003). These gas outflows can have different origins, such as being jet-driven (if the object is radio loud) or related to starburst and AGN winds.

Why should we expect gas outflows also in radio galaxies? In these objects all the potential drivers for powerful outflows (a highly luminous ionising AGN, relativistic jets and, often, a starburst) are present to varying degrees. In particular, the activity-inducing processes (e.g. merger, interaction) are believed to involve the injection of substantial amounts of gas/dust into the central nuclear regions. Thus, we can expect that in the first phase (or in a re-started phase) of activity, strong interactions with the relatively dense medium will occur. Indeed, gas outflows are now increasingly detected in radio galaxies and here we present a summary of the results we have obtained so far in our study of both the ionized, as well as the neutral, components of such outflows.

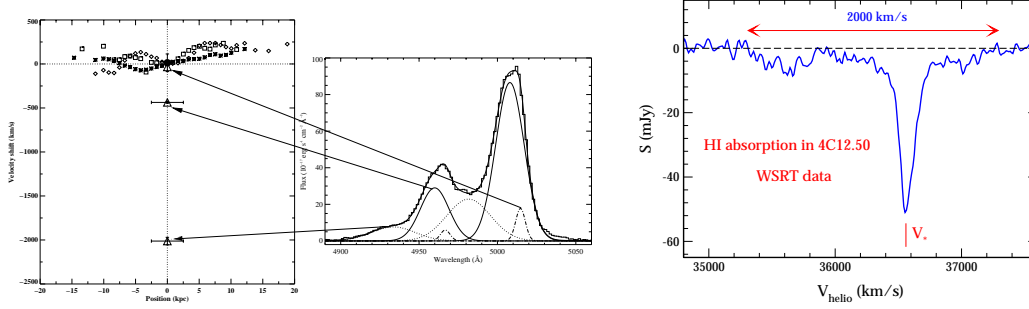


Figure 1. *Left* Radial velocity profile of the extended gaseous halo of 4C12.50. Key: \*,  $\diamond$  and  $\square$ : highly extended [O II] emission (narrowest component);  $\bullet$ : HI 21-cm absorption;  $\triangle$ : 3 components of [O III] in the nucleus. The [OIII] profile with the components from the fit is also shown. *Right* The HI absorption profile detected in 4C 12.50 from the WSRT observations. The spectra are plotted in flux density (mJy) against optical heliocentric velocity in  $\text{km s}^{-1}$ .

## 2. Outflows of ionized gas

The first clear example of an outflow of ionized gas that we have found is in the southern *starburst* radio galaxy PKS 1549–79 (i.e. a radio galaxy that spectroscopically shows a young stellar population component in addition to the old stellar component typical of elliptical galaxies). In PKS 1549–79, different redshift systems associated with both the low- and high-ionisation emission lines were found (Tadhunter et al. 2001). The high ionisation lines are broader, with  $\text{FWHM} > 1000 \text{ km s}^{-1}$  while the low-ionisation lines are narrower. The HI absorption detected in this object (Morganti et al. 2001) has the same redshift as the low ionisation gas, while the high ionisation gas appears blueshifted with respect to it. The HI absorption and the low ionisation gas are associated with a cocoon of material surrounding the tiny ( $\sim 200 \text{ pc}$  in size) radio source. On the other hand, the high ionisation (and blueshifted) gas is believed to be associated with an outflow from a region close to the radio jet and disturbed by it. Taken together, all these results are consistent with the idea that PKS 1549–79 is a young radio source in which the cocoon of debris left over from the event that triggered the activity has not yet been swept aside by circumnuclear outflows. More recently, Bellamy et al. (2003) have detected broad  $\text{Pa}\alpha$  in PKS 1549–79 confirming that this object indeed contains a quasar nucleus that is moderately extinguished, despite evidence that its radio jet points close to our line-of-sight.

An even more extreme case of gas outflow has been found in the radio galaxy 4C 12.50 (PKS 1345+12). This is a particularly interesting object as it is a prime candidate for the link between ultraluminous infrared galaxies (ULIRGs, Sanders & Mirabel 1996) and radio galaxies (Evans et al. 1999). The radio source is confined to a region  $< 0.1 \text{ arcsec}$  ( $\sim 240 \text{ pc}$ ) and has all the characteristics of young radio sources ( $< 10^7 \text{ yr}$ ). The ISM of this radio galaxy is extremely rich: it is the brightest far-IR radio galaxy and has a high molecular gas mass

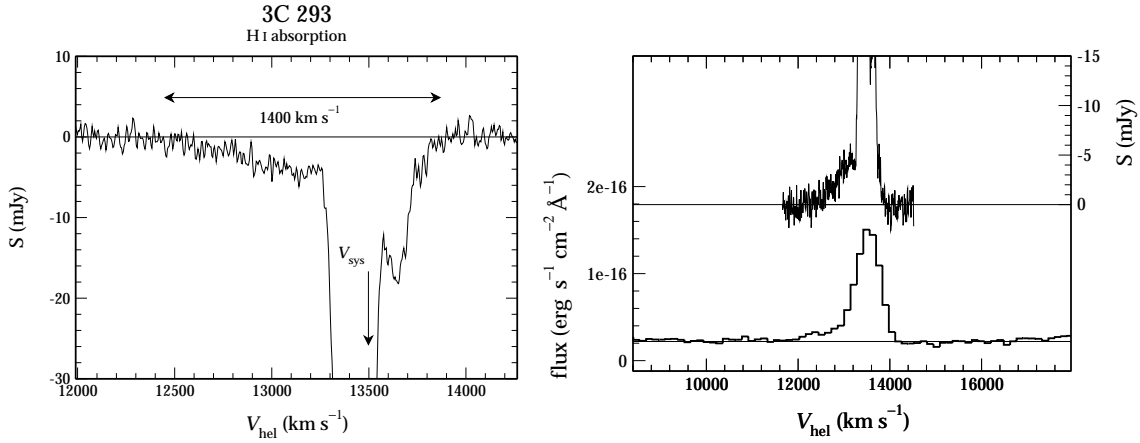


Figure 2. *Left* A zoom-in of the HI absorption spectra of 3C 293 clearly showing the broad HI absorption. The spectra are plotted in flux (mJy) against optical heliocentric velocity in  $\text{km s}^{-1}$ . *Right* Comparison between the HI absorption (top) and the [OII]3727Å (bottom, from Emonts et al. in prep.) profiles in the radio galaxy 3C 293. The similarity of the broad, blueshifted wing in the two profiles is evident.

(Evans et al. 1999). Long slit spectra were taken (using the WHT, see Holt et al. 2003 for details) in order to investigate the impact of the nuclear activity on the circumnuclear interstellar medium. The spectra show extended line emission up to  $\sim 20$  kpc from the nucleus, consistent with the presence of an asymmetric halo of diffuse emission as observed in optical and infrared images.

At the position of the nucleus, complex emission line profiles are observed and Gaussian fits to the [OIII] emission lines (see Fig. 1 *left*) require three components (narrow, intermediate and broad), the broadest of which has  $\text{FWHM} \sim 2000 \text{ km s}^{-1}$  and is blueshifted by  $\sim 2000 \text{ km s}^{-1}$  with respect to the halo of the galaxy and the deep and narrow HI absorption. This component is interpreted as material in outflow. A large reddening and high density ( $n_e > 4200 \text{ cm}^{-3}$ ) has also been found for the most kinematically disturbed component. 4C 12.50, like PKS 1549-79, appears, therefore, to be a young radio galaxy with nuclear regions that are still enshrouded in a dense cocoon of gas and dust. The radio jets are now expanding through this cocoon, sweeping material out of the nuclear regions (Holt et al. 2003).

### 3. Outflows of neutral hydrogen

Extremely intriguing is the discovery of a number of radio galaxies where the presence of fast outflows is associated not only with ionized but also with *neutral* gas. This finding gives new and important insights on the physical conditions of the gaseous medium around an AGN.

The best example found so far of this phenomenon is the radio galaxy 3C 293 (Morganti et al. 2003a). In this galaxy, very broad HI absorption has been detected against the central regions - this is in addition to the known and

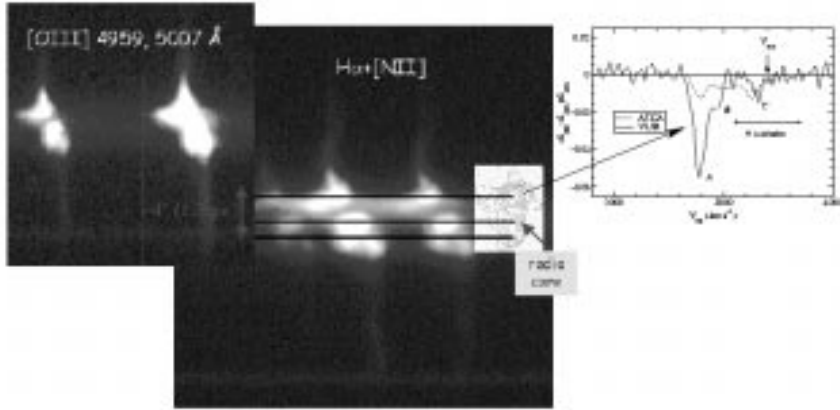


Figure 3. *Left:* a zoom-in of the [OIII] and H $\alpha$ + [NII] lines in the Seyfert IC 5063. The radio image on similar scale is also shown. The highly blueshifted component close to the bright radio lobe is clearly visible. *Right:* HI absorption profile profile detected against the NE radio lobe (from Oosterloo et al. 2000).

much narrower absorption; Haschick & Baan 1985, Beswick et al. 2002. The absorption profile, obtained using the new broad band (20 MHz) system available at the Westerbork Synthesis Radio Telescope, has a full width at zero intensity of about  $1400 \text{ km s}^{-1}$  and most of this broad absorption ( $\sim 1000 \text{ km s}^{-1}$ ) is blueshifted relative to the systemic velocity. The broad absorption is shallow (the optical depth is only  $\sim 0.15 \%$ ) and corresponds to a column density of the HI of  $\sim 2 \times 10^{20} T_{\text{spin}}/100 \text{ K cm}^{-2}$ . This is likely to be a lower limit to the true column density as the  $T_{\text{spin}}$  associated with such a fast outflow can be as large as a few 1000 K (instead of 100 K which is more typical of the cold, quiescent HI in galaxy disks). This absorption represents a fast outflow of *neutral* gas from the central regions of this AGN. New optical spectra (see Fig. 2b, from Emonts et al. in prep.) show that the optical emission lines also contain a broad component that is very similar to the broad HI absorption. This suggests that the HI and ionized gas outflows may be coming from the same physical region.

The radio galaxy 4C 12.50 also shows broad HI absorption (shown in Fig. 1b) when observed using a broad radio band. The absorption appears complex and *extremely broad*. The full range of velocities covered by the HI absorption is  $\sim 2000 \text{ km s}^{-1}$ , *the broadest detected so far in HI*. The peak optical depth of the broad component is only  $\tau \sim 0.002$  and the column density of the full system of shallow HI absorption (assuming a covering factor is 1) is  $\sim 1.7 \times 10^{20} T_{\text{spin}}/100 \text{ K cm}^{-2}$ .

### 3.1. Origin of the HI outflows

The central question is how *neutral* gas can be associated with such fast outflows. As discussed in Morganti et al. (2003a) for 3C 293, a number of possible

hypotheses can be made about the origin of such outflows. They include, e.g., starburst winds (Veilleux et al. 2002), radiation pressure from the AGN (Dopita et al. 2002), jet-driven outflow and adiabatically expanding broad emission line clouds (Elvis et al. 2002).

The model that we favour is jet-driven outflow, although we cannot rule out that one of the other mechanisms is also at work at some level. This model assumes that the radio plasma jet hits a (molecular) cloud in the ISM. As a consequence of this interaction, the kinematics of the gas are disturbed by the shocks and the gas is ionized by it. Once the shock has passed, part of the gas may have the chance to recombine and become neutral while it is moving at high velocities. One problem with this model (considered in detail by Mellema et al. 2002) is that it may not be possible to accelerate the clouds of gas to the high velocities that we observe, as indicated by e.g. the simulations presented by van Breugel (these proceedings).

To understand which is the more likely mechanism, we now need high spatial resolution observations to find the exact position of the absorption. So far this information is available only for the Seyfert galaxy IC 5063 where it is providing evidence that the interaction between the radio jet and a molecular cloud is indeed the cause of the gas outflow.

### 3.2. The case of the Seyfert galaxy IC 5063

The southern Seyfert galaxy IC 5063 was the first AGN where a fast outflow of neutral hydrogen was detected (Morganti et al. 1998). VLBI observations have confirmed that the broad absorption is detected against the bright radio lobe (i.e. *not* against the nucleus) situated at  $\sim 1.3$  kpc from the nucleus, as shown in Fig. 3a (see also Oosterloo et al. 2000).

Deep optical spectra have been taken with the ESO-NTT to compare the kinematics of the ionized gas with that of the neutral hydrogen component in order to study the mechanism that could drive this outflow. Preliminary results are presented in Morganti et al. (2003b). The data reveal extremely complex gas kinematics as can be seen in Fig. 3b. This includes the presence of an outflow of ionised gas (with velocities of several hundred km/s) at the location of the brighter radio lobe. The amplitude of this outflow is strikingly similar to that of the H I. Because of its location, we consider the interaction between the radio jet and the ISM to be the most likely mechanism for the extreme kinematics.

## 4. Conclusions

Our observations show that gas outflows of both ionized gas and neutral hydrogen are found in some radio galaxies. So far the indications are that these outflows are present in objects that are either in the early-stage of their evolution (like 4C 12.50) or, perhaps, in a phase of re-started activity (as we think it is the case for 3C 293). Moreover, another characteristic that appears to be common among these objects is the presence of a young stellar population component (Tadhunter et al. 2003).

Although it is difficult to attribute the outflow to a starburst wind (as the young stellar population is usually relatively old, 0.5-2 Gyr), the presence of such a young stellar component could be an indication that the galaxy is indeed

in a particular stage of its evolution, where large amounts of gas/dust - likely from the merger that triggered the activity - are still present in the inner region and the radio jet is strongly interacting with it.

A more systematic search for fast gas outflows in radio galaxies is now in progress.

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